Experimental Tests for Seismic Assessment and Strengthening of Adobe Structures

C. Oliveira, H. Varum, A. Figueiredo, D. Silveira & A. Costa
Universidade de Aveiro, Aveiro, Portugal

ABSTRACT:
Adobe structures present very appealing characteristics regarding a more sustainable practice with the preservation of our natural resources. However, when subjected to cyclic horizontal actions, such as earthquakes, they can present a deficient behaviour.
With the purpose of evaluating the seismic vulnerability of adobe structures, a series of tests were conducted on a full-scale adobe wall considering constant dead and live loads combined with cyclic horizontal actions with rising amplitude. A structural strengthening solution was tested on the repaired wall after its assessment test. The adopted repair solution, based on cracks injection, combined with the strengthening solution, proved to be very efficient in improving the performance of the adobe wall.
With the study conducted, it was possible to contribute to the characterization of adobe structural walls in terms of deformation capacity and failure modes, establishing the basis for the calibration of numerical models for adobe structures.

Keywords: Seismic assessment, Adobe structures, Experimental tests, Strengthening

1. INTRODUCTION

Earth has been used in construction since ancient times due to cultural, climatic and economic reasons. In fact, this kind of materials presents qualities such as low cost, local availability and recyclability, which allow a more sustainable construction practice, with the preservation of our natural resources. In addition, this type of construction is associated to quite simple construction methods that require small quantities of energy. However, this type of material presents low tensile strength and fragile behaviour, and can thus cause a deficient response to horizontal actions. Particularly when subjected to cyclic horizontal actions, such as earthquakes, this kind of structures present a deficient behaviour, which may cause significant human losses and important structural damage.
In order to provide an adequate resistance to earth structures, it is necessary to complement the utilization of the traditional construction materials with innovative and inexpensive strengthening techniques which may allow reducing the seismic vulnerability of this type of constructions.
In Portugal, Aveiro region holds many examples of adobe structures. Built until the middle of the XX century, many adobe buildings of this region represent a valuable and important architectural, cultural and historical patrimony. At the present time, a high percentage of these buildings are inadequately maintained by reasons of non-conservation or incorrect rehabilitation interventions. In effect, due to the loss of the traditional knowledge on the construction of these types of structures, many of the interventions conducted apply materials or rehabilitation solutions that, instead of improving the overall structural performance, reduce it. In addition, Aveiro is a region with moderate seismic hazard. The poor maintenance conditions along with high seismic vulnerability of these structures demand more research and the development of seismic strengthening solutions.
Several research studies have been conducted ([Arêde et al.; 2007], [Silveira et al.; 2007], [Silveira, D.; in progress], [Varum et al.; 2008], [Varum et al.; 2005]) to suppress the existent lack of information, relatively to the structural properties of adobe and its constituting materials, such as

composition, resistance and stiffness, ductility, energy dissipation capacity and collapse mechanisms. The Civil Engineering Department of Aveiro University, in Portugal, has recently been developing several scientific studies on the behaviour of adobe structures existent in Aveiro district. The research was initially focused on the characterization of constitution materials, with analysis of their composition, adobe blocks strength, stiffness, ductility and energy dissipation capacity. A meticulous evaluation regarding frequent causes of structural and non-structural pathologies in adobe masonry is currently being developed [Silveira. D.; in progress]. These studies, along with structural tests on adobe walls ([Arêde et al.; 2007], [Figueiredo, A.; 2009], [Pereira, H.; 2008], [Varum et al.; 2005], [Varum et al.; 2008], [Varum et al.; 2007]), have been providing important information regarding future guidelines for the development of reinforcement and rehabilitation solutions for seismic resistant adobe structures.

2. EXPERIMENTAL TESTS

In the Laboratory of Civil Engineering Department of Aveiro University, a real-scale adobe wall was built with an “I” shape in a plan view (Figure 2.1). Its construction used adobe blocks with average dimensions of 28x45x12 cm^3, from a demolition in Aveiro region. In order to simulate an adobe construction representative of the vast patrimony existent in the district, a mortar using hydraulic lime was chosen. The joints mortar used was composed by hydraulic lime and arenaceous soil. The plaster had the same composition. The wall was built with a height of 3,07m, a length of 3.5m and a mean thickness of 0.29m [Pereira, H.; 2008].

a) b)

Figure 2.1. Adobe wall construction: a) beginning of the construction; b) final phase of the construction (before plastering)

2.1 Tests on the original non strengthened wall

The wall was initially constructed without strengthening, and was tested for a cyclic horizontal force of increasing amplitude until failure. The force was applied at 2.5m high from the base of the wall (Figure 2.2). In addition, and in order to simulate other dead and live loads corresponding to the quasi-permanent combination, a vertical uniform load was placed on top of the wall, with a total value of 20kN. The deformation of the wall during the test was registered in several points through transducers placed at the most representative response points of the wall.

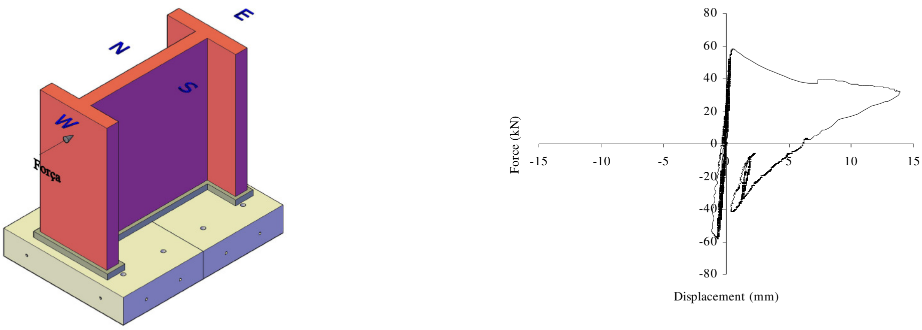


Figure 2.2. Schematics of the experimental test

Figure 2.3. Force versus displacement at the application force point

The maximum shear capacity obtained in the cyclic test was 58kN, for a horizontal displacement of 1mm at the top of the wall. Figure 2.3 shows the evolution of the horizontal force with the corresponding displacement at the point of force application.
As seen in Figure 2.3, after the cyclic test and corresponding to a maximum lateral displacement of 13.7mm at the point of load application, a residual strength of 30kN was observed.
At the end of each cycle series the test was stopped and dynamic tests were performed. Accelerations were measured through a seismograph placed at a niche on top of the wall. The first longitudinal natural frequency of the wall was determined with FFT at the end of each cycle test series (Table 2.1 and Figure 2.4).

Table 2.1. Frequencies registered during tests

Test number	Description	Frequency (Hz)
1	Original wall after vertical load application	23.00
2	After 1st cycle of 0.1mm (0.004% drift)	21.48
3	After 1st cycle of 0.5mm (0.02% drift)	20.51
4	After 1st cycle of 1.0mm (0.04% drift)	18.07
5	After 1st cycle of 14.0mm (0.56% drift)	15.63

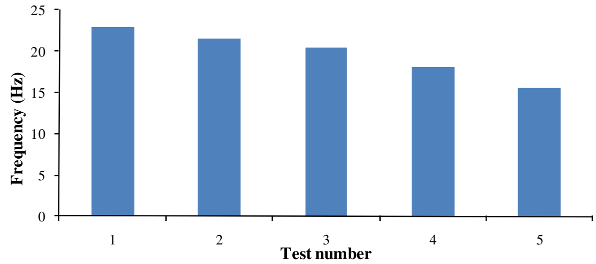


Figure 2.4. Evolution of the first natural frequency of the wall during the cyclic destructive test

The results obtained allowed to derive the following observations:

- The first natural frequency of the wall, with the additional vertical load, is 23.00Hz;
- After the cyclic loading of 0.1mm and 0.5mm, the frequency dropped to 21.48Hz and 20.51Hz, correspondingly;
- After reaching the maximum strength of the wall, for a horizontal displacement of 1mm, the frequency decreased to a value of 18.07Hz;
- In the end of all the cyclic tests, the frequency decreased again to a final value of 15.63Hz.

Simultaneously with the experimental tests on the wall, mortar specimens with dimensions of 16x4x4cm^3 were tested. The average compressive strength obtained was 0.67MPa. The results for the tensile strength were approximately 35% of the corresponding compression strength.

2.2 Tests of the strengthening solution materials

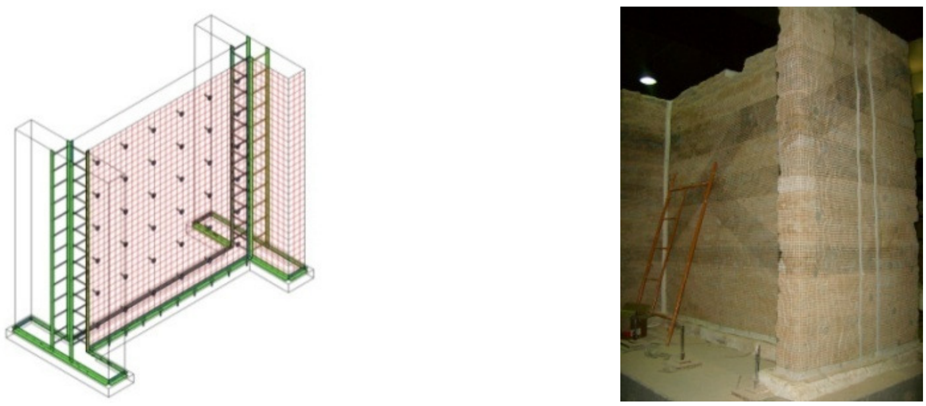
With the purpose of restoring the original strength of the wall, improving also its ductility, the possible materials and strengthening solutions were compiled (more detailed information in [Figueiredo, A.; 2009]).
During the construction of the wall, as stated before, only traditional materials were used, as one of the objectives was to correctly portray the existent traditional adobe buildings. Therefore, the repairing solution had to consider components with a good compatibility to these traditional materials. In addition, an inexpensive repairing scheme was desirable. Three different compositions were studied for the grout to be used in the cracks injection: air lime, hydraulic lime and a mixture of both limes referred in the proportion of 1:1. Furthermore, a synthetic mesh was applied involving the wall, for its strengthening.
In order to evaluate the efficiency of the repairing and strengthening solutions chosen, tests to the grout and to the mesh were conducted.
The tensile bending strength of the adobe blocks (Figure 2.5) was studied before and after fissure closing, with a three-point bending test. Firstly, original adobe blocks were tested until failure. The average tensile strength obtained was 0.54MPa. Afterwards, and in order to assess the most effective

repairing solution, the cracks formed during the test were closed with the three different compositions considered.
The hydraulic lime grout allowed a much more efficient bonding, when compared with the other 2 solutions. Thus, this was the composition chosen to fill the wall cracks.
Regarding the mesh selected to be used in the strengthening of the wall, there was no technical information describing its mechanical behaviour. There was therefore the need of conducting some tests. In order to estimate the influence of the mesh in the wall retrofitting when incorporated in the plaster, its tensile behaviour was experimentally evaluated.
Figure 2.4 shows the tensile test of the synthetic mesh. The medium tensile strength obtained was 9MPa for a longitudinal deformation of 18%.

Figure 2.4. Tensile test of the synthetic mesh

2.3 Damage repairing and wall strengthening

After the initial series of cyclic tests on the original wall, the damages were repaired by filling the cracks, injecting hydraulic lime grout under pressure. Then, the original plaster was removed in order to apply the synthetic mesh involving the wall. The mesh was fastened through PVC leg angle sections joined together by a nylon filament in all the concave vertexes of the wall (Figure 2.6). Additionally, plastic nails were also tacked forming a square net of fixed points, 0.5m apart in both directions (Figure 2.6). Finally, the wall was plastered, using a mortar with a composition similar to the original one.



a) b)

Figure 2.6. Wall strengthening: a) general schematics; b) synthetic mesh fastening

2.4 Tests on the retrofitted wall

In order to allow an easier comparison of the results, the same test layout was used for the repaired and strengthened adobe wall.

The lateral displacements imposed on the wall with increasing amplitude caused an evolution of the damages, beginning with the propagation of small cracks until the detachment of the plaster in local areas (Figure 2.7). The fissures were only perceptible after a lateral displacement of 5mm. The following cycle, with a maximum imposed displacement of 12.5mm, heightened and intensively propagated the cracks already installed. Many new fissures were also formed with apertures between 0.5 and 1.0mm. Subsequently, for imposed displacements of 25.0 and 37.5m, a large detachment of the plaster happened in a highly cracked area. Next to the application point of the concentrated horizontal force, it was observed crushing. Figure 2.8 displays the plaster detachment during the last cycles of imposed displacements. It is also possible to observe the cracks that trespass the wall.

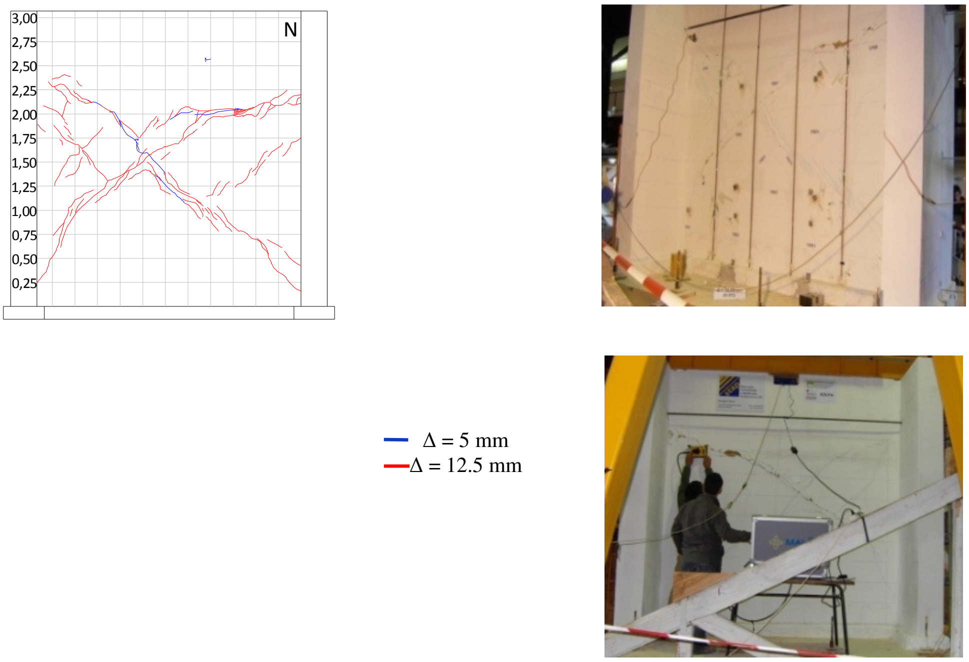


Figure 2.7. Damage evolution (North and South faces)

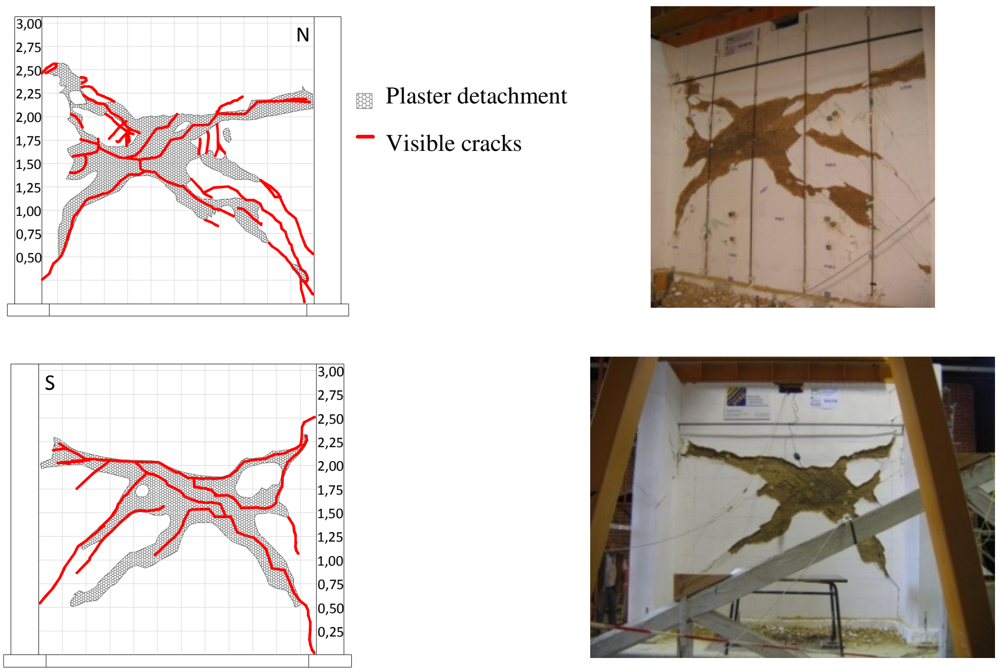
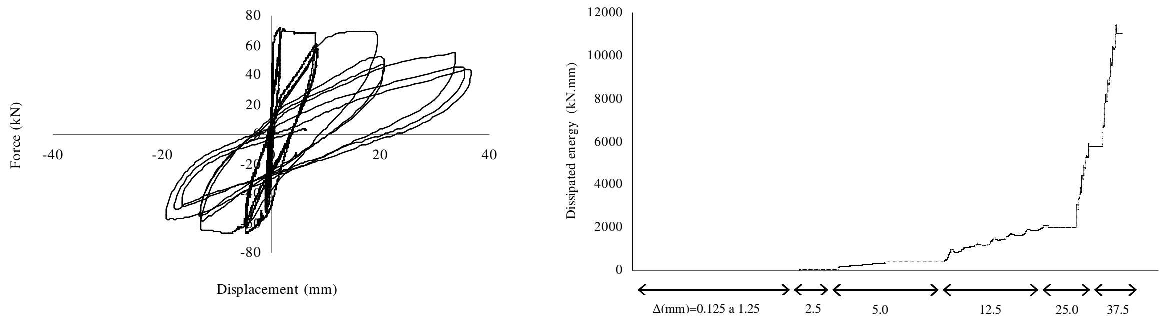


Figure 2.8. Final damage state (North and South faces)

Figure 2.9 shows the global results of the cyclic test on the retrofitted adobe wall, namely in terms of force-displacement and evolution of dissipated energy. As in the previous tests on the original non-strengthened wall, the cyclic lateral displacements were imposed in-plane of the wall.



a) b)

Figure 2.9. Global test results: a) lateral force versus displacement; b) dissipated energy evolution

The capacity of the wall to lateral shear was found to be 71.75kN, for a displacement of approximately 1.6mm. The maximum lateral displacement imposed to the wall during the cyclic test was ca. 40mm. The residual strength of the wall was of 43.46kN, value that corresponds to a decrease of 40% related with its maximum strength. As it can be seen in Figure 2.9-b), only in the final phase of the test (for imposed lateral displacement superior to 12.5mm) there is a significant dissipation of energy.

Figure 2.10 presents the results in terms of force versus displacement obtained for the original wall and for the strengthened reinforced wall.

The strengthened wall presented an initial stiffness very close to the one of the original wall. The maximum shear capacity had an increase of approximately 25% and the maximum lateral displacement imposed was approximately the double of the one applied on the original wall. The analysis of the post-peak strength reduction, for the original and strengthened walls, reveals that the fragility observed in the original wall was significantly decreased with the strengthening solution adopted, increasing its ductility and the energy dissipation capacity.

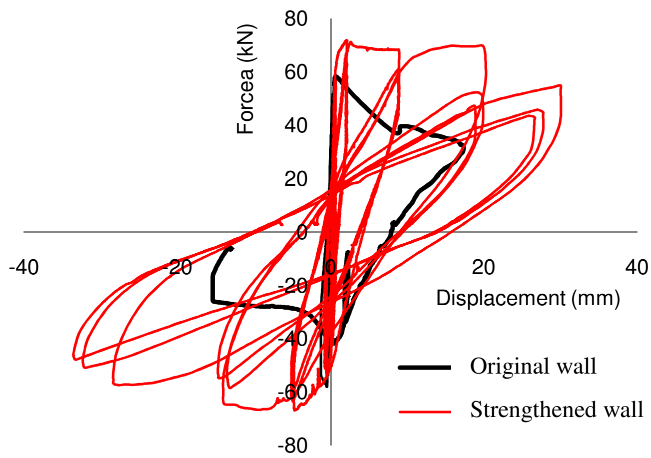


Figure 2.10. Horizontal force versus displacement: original and strengthened wall

The first natural frequency of the strengthened wall was derived, based on acceleration measurements registered before, during and after the cyclic destructive text. The results obtained are presented in Figure 2.11.

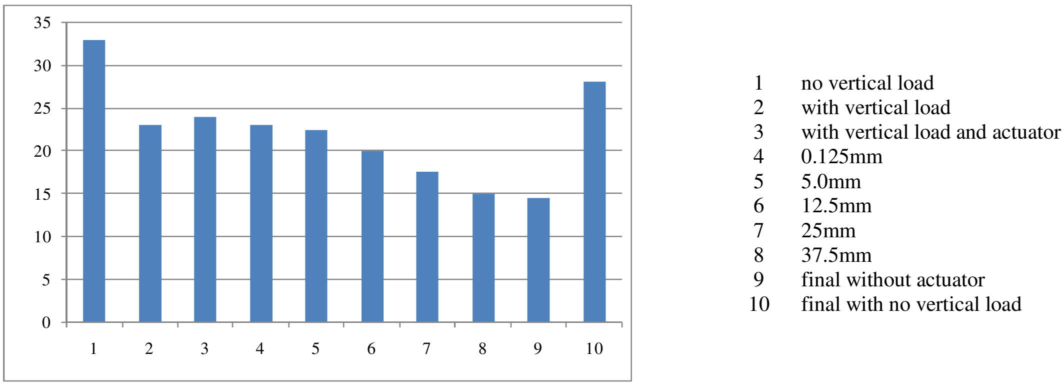


Figure 2.11. Evolution of the strengthened wall first natural frequency

The evolution of the first natural frequency, for both walls, original and strengthened, is displayed in Figure 2.12, as a function of the maximum displacement imposed. The stiffness decrease during the cyclic test on the strengthened wall is smoother, which causes an also smoother decrease on the first natural frequency. The rehabilitation of the wall provided and initial stiffness close to the one of the original non-damaged wall.

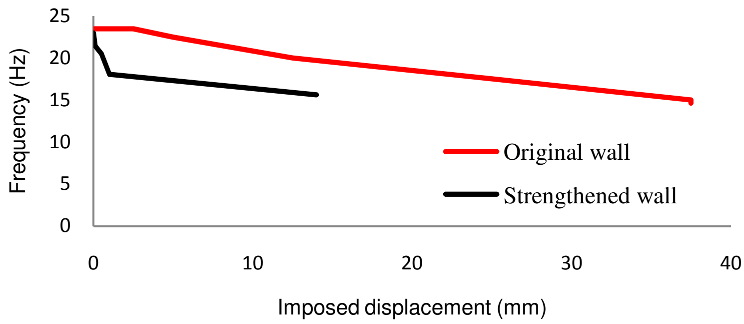


Figure 2.12. First natural frequencies evolution on the original and strengthened walls

3. CONCLUSIONS

A real-scale adobe wall was built and tested under cyclic horizontal loads. Afterwards, a strengthening solution was applied and the strengthened wall was tested. This study provides information contributing for the comprehension of the behaviour of adobe masonry structures, under cyclic solicitation, as the induced by earthquakes. It was possible to characterize the evolution of the response in terms of force-displacement, maximum admissible deformation, as well as the typical collapse modes corresponding to the studied adobe wall.

All the materials used, for the construction, repair and strengthening, were tested in laboratory. The preparation of all materials and the rehabilitation execution of the wall were all conducted in laboratory, and thus there was a rigorous control of all the materials and techniques used.

The solution for filling the wall cracks (injection of hydraulic lime grout) combined with the strengthening solution (synthetic mesh incorporated in the plaster) proved to be very effective.

The tests on the retrofitted wall demonstrated that the wall was able to recover its initial stiffness. Moreover, the lateral strength increased slightly, and the ductility and the energy dissipation capacity improved significantly. After the rehabilitation, it was not observed a fragile rupture, which is typical in this kind of masonry. The strengthening solution was able to improve the structural performance of the wall, decreasing its seismic vulnerability.

To sum up, the study developed provides more insight in the interpretation of the typical structural pathologies, allowing a more rigorous evaluation of the adobe structures safety. Also, the rehabilitation solution studied proved to be viable for possible application in the strengthening of adobe constructions in seismic areas, reducing their vulnerability.

Acknowledgments
The authors would like to express their gratitude to everyone who contributed in making this study possible, with a special thanks to:
- Laboratory of Earthquake and Structural Engineering (LESE), Faculty of Engineering, Porto University, Portugal
- STAP company
- Aveiro City Council
- Phisycs, Mechanics and Geological Sciences departments of Aveiro University

REFERENCES

Arêde, A.; Costa, A.; Varum, H.; Vicente, R.; Costa, A.; Pereira, H.; Rodrigues, H. (2007) Avaliação experimental do comportamento fora do plano de paredes de alvenaria de adobe. V Seminário Arquitectura de Terra em Portugal, Departamento de Engenharia Civil, Universidade de Aveiro, Aveiro, Portugal *(in portuguese)*

Blondet, M.; Garcia, G.; Brzey, S. (2003) Construcciones de adobe resistentes a los terremotos. Marjorie Greene, EERI. Abril de 2003

Figueiredo, A. (2009) Caracterização de uma solução de reforço sísmico de paredes de adobe. Civil Engineering Master Thesis, Universidade de Aveiro, Aveiro *(in portuguese)*

Pereira, H. (2008) Caracterização do comportamento estrutural de construções em adobe. Civil Engineering Master Thesis, Universidade de Aveiro, Aveiro *(in portuguese)*

Silveira, D.; Varum, H.; Costa, A. (2007). Rehabilitation of an important cultural and architectural heritage: the traditional adobe constructions in Aveiro district, Sustainable Development III, April 25-27, Editors A. Kungolas, C.A. Brebbia, E. Beriatos - WITPress, ISBN: 978-1-84564-103-0, Vol.s 1 and 2, pp. 705-714, Carvoeiro, Portugal

Silveira, D. *(in progress)* Avaliação da vulnerabilidade sísmica e reabilitação de construções existentes em adobe. PhD Thesis in Civil Engineering (currently being developed), Universidade de Aveiro, Aveiro *(in portuguese)*

Varum, H.; Costa, A.; Pereira, H.; Almeida, J.; Rodrigues, H. (2008) Caracterização do comportamento estrutural de paredes de alvenaria de adobe, Revista Mecânica Experimental, APAET – Associação Portuguesa de Análise Experimental de Tensões, ISSN 1646-7078, Vol. 15, pp. 23-32, 2008 *(in portuguese)*

Varum, H.; Martins, T.; Velosa, A. (2005) Caracterização do adobe em construções existentes na região de Aveiro. IV SIACOT Seminário Ibero-Americano de Construção com terra e III Seminário Arquitectura de Terra em Portugal. Convento da Orada. Monsaraz, Portugal *(in portuguese)*

Varum, H.; Costa, A.; Silveira, D.; Pereira, H.; Almeida, J.; Martins, Tiago. (2007). Structural Behaviour Assessment and Material Characterization of Traditional Adobe Constructions, AdobeUSA 2007, May 18-20, NNMC and Adobe Association of the Southwest, El Rito, NM, USA